

Aerodynamic Performances of Paper Planes

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ABSTRACT

Paper plane has a high potential to be upgraded as a Micro Air Vehicle (MAV). Due to its simplicity, paper plane offers easier design option compared to the biological inspired designs as shown in recent MAV development. However, researchers have underestimate and overlook the basic aerodynamic performance induced by these paper planes. This is due to its common usage as toys and wide range of paper plane design. Thus, the objective for current work is to analyse and compare the aerodynamics forces and its performance for selected paper plane design known as Glider, Wide Stunt Glider Plane and Stunt plane. A series of CFD simulations on each paper plane was executed by using ANSYS-CFX module. A steady state, incompressible flow Navier-Stokes equation (RANS) combined with Shear Stress Turbulence (SST) model were used in this works to solve flow problem over the paper planes. The analysis is mainly conducted to study and compare the lift coefficient (C_L), drag coefficient (C_D) and aerodynamic efficiency (C_L/C_D) performances for each paper planes. The C_L results show that the Glider paper plane has managed to produce better C_L performances in terms overall C_L magnitude, stall angle, wider angle of attack (α) envelope and higher maximum lift coefficient magnitude compared to the other paper plane design. However, Glider paper plane has the least C_D distributions by producing at least 14.3% larger C_D magnitude compared to the other plane design at certain α region. Instead, The Wide Stunt has promisingly produced better C_D distribution by producing lower C_D value compared to the other plane design. Based on C_L/C_D performance, the Wide Stunt paper plane has produced better C_L/C_D and maximum aerodynamic efficiency ($C_L/C_{D\max}$) magnitudes compared to the other design. Wide Stunt paper plane induced at least 6.4% better $C_L/C_{D\max}$ magnitude compared to the other paper plane design. Based on these results, it can be concluded that Wide Stunt paper plane has promising advantages which are very crucial for the paper plane especially during hovering operation, take-off, and landing manoeuvre.

Keywords:

Aerodynamics Performances; Paper Plane; MAV

1. Introduction

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Paper planes are seen as toy figures that give inspiration in the aeronautical engineering studies which led to a variety of plane design. Indeed, paper planes offer less weight and cost which can be folded based on standard origami technique for any desired shape [1]. The less weight concept is parallel with the MAV wing objective which is very crucial to be achieved. Unlike larger systems, MAVs are usually built based on lightweight material stock such as balsa wood [2], injection moulded plastics [3] or even aluminium sheet [4]. However, such materials require substantial processing to fabricate aerodynamic structures [5].

Paper is a biodegradable cellulose fibre sheet which is disposable [6], sturdy and low-cost [5]. Paper consists of a matrix of interlinked cellulose fibers which is a knit structure. The knit structure gives paper good tensile performance and formability with low bulk weight. A low-stiffness hinge can be formed when paper is bent [7]. Even simple bending and forging operations are sufficient to make permanent deformations to the shape of a paper structure, greatly reducing processing cost. At low production input, paper offers an exceptional strength to weight ratio with additional desirable aeroelastic properties [4]. The origami paper plane has been long regarded as flying toys and it can be easily fabricated from paper. Thus, the cellulose material has a bright future to be explored as a potential material for disposable MAV options [5].

Paper planes flying in the same Reynolds-number regime as MAV, thus paper planes have a high potential to be upgraded as MAV. Due to its simplicity, paper planes offer easier design options compared to the biological inspired designs as shown in recent MAV development [8-9]. Despite its huge potential through a wide range of origami design [10] and experimental test cycles, researchers have underestimated and overlooked the basic performance of lift and drag induced by these paper planes. This is due to its common usage as toys and wide range of paper plane design. Thus, the objective for current work is to analyze the lift and drag performance for the selected paper plane designs. In this work, three different designs of paper planes were selected as a basic paper plane design. The design selection was made based on its common usage as paper plane toys and recommendation to be used with PowerUp 3.0 device [11]. Each of the paper planes will be analyzed through CFD simulation before the comparison study on lift and drag performance among the planes executed.

2. Methodology

2.1 Paper Plane Design Selection

There are three different paper plane designs that have been selected for current works. The selection is made based on its popular usage as paper plane toys and recommendation to be used with PowerUp 3.0 device. PowerUp 3.0 [11] is a device that can remotely control a paper airplane through a Bluetooth® connected smartphone. This device has huge potential to convert the paper plane into MAV class. The three selected paper plane designs are known as The Glider, Stunt Plane and Wide Stunt Glider paper plane. The CAD drawing of each paper plane design is shown in Figure 1 to Figure 3. The overall wing dimension, aspect ratio and calculated velocity for each paper plane is given in Table 1. The velocity of each paper plane is determined based on equivalent Reynolds Number at chord, $Re = 100,000$

2.2 CFD Simulation

The CFD simulation on each paper plane was executed by using ANSYS-CFX module. The computational air domain was built around the morphing MAV wing, in which the symmetrical condition is exploited by modelling only half of the computational domain. The air domain is built

surrounding the symmetrical paper plane and sized based on the root chord as shown in Figure 4. The boundary conditions imposed on the air domain are also shown in Figure 4. The grid independent test results show that the optimized grid for each paper plane achieved around 300,000 tetrahedrons mesh elements as shown in Figure 5. The symmetrical wall and side wall are assigned as symmetrical boundary condition and slip surface boundary condition respectively.

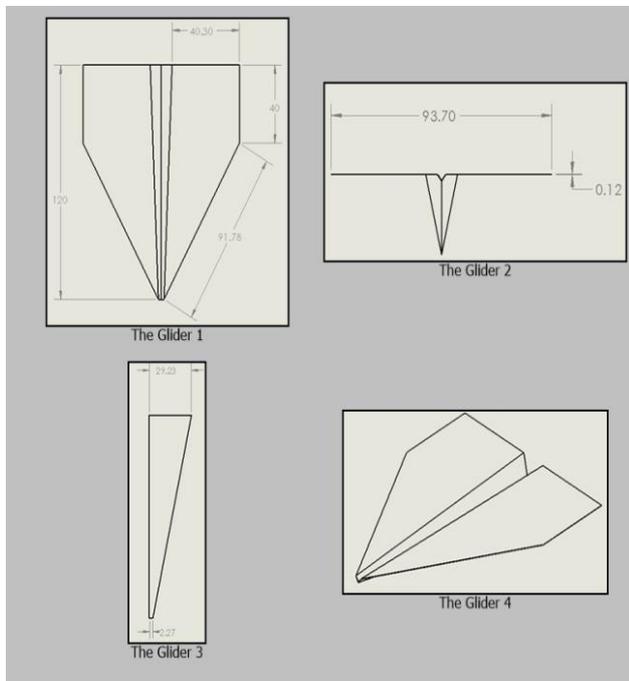


Fig. 1. The Glider paper plane

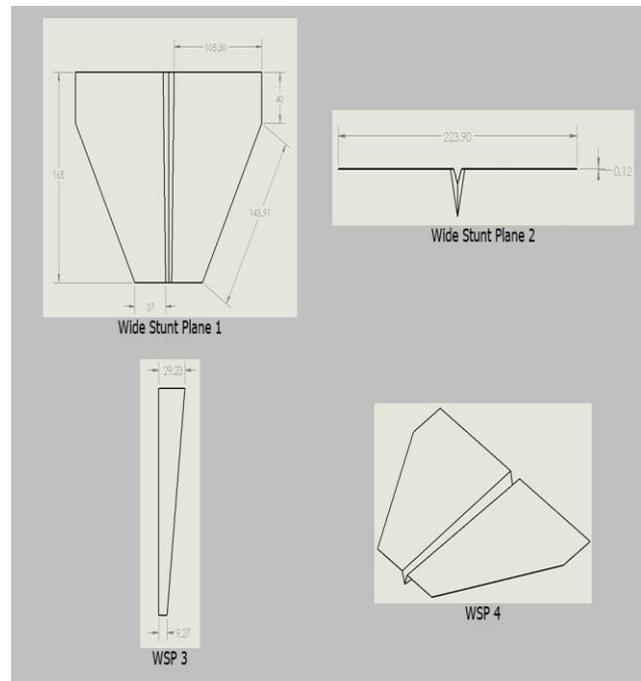


Fig. 2. The Wide Stunt Glider paper plane

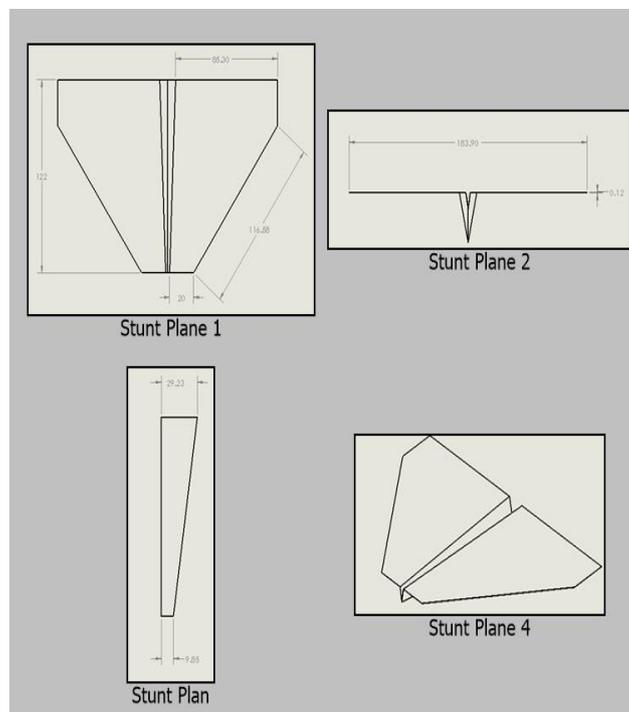


Fig. 3. Stunt Paper plane

Table 1
 The basic dimension of the paper plane designs

Paper plane	The Glider	Wide Stunt Glider	Stunt Plane
Cord length (c)	121mm	166mm	123mm
Wing area (S)	31.3cm ²	131.7cm ²	74.5cm ²
Aspect ratio (AR)	2.79	3.79	3.59
Velocity (U)	12.5 m/s	8.6 m/s	11.7 m/s

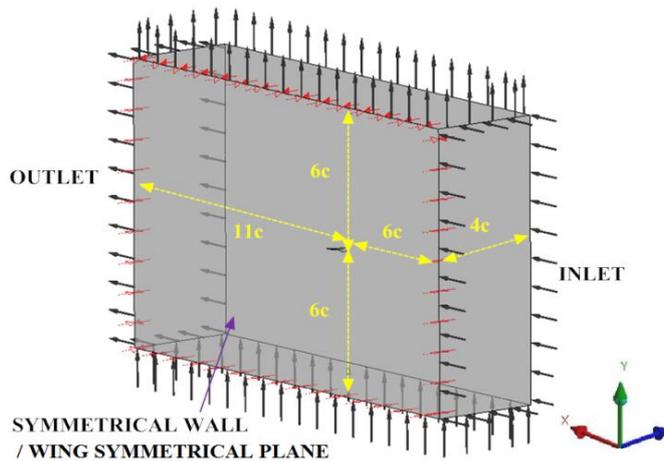


Fig. 4. Air domain sizing and boundary condition imposed on air domain

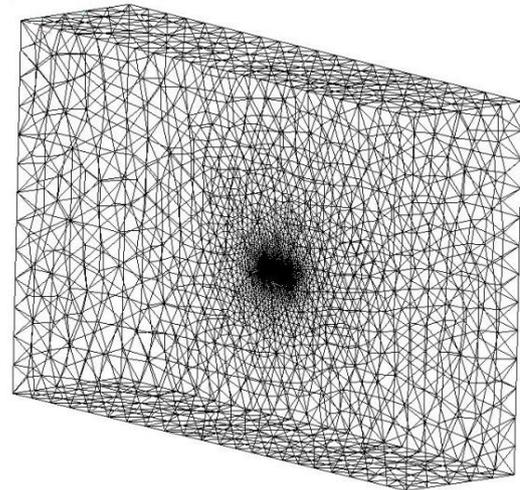


Fig. 5. The optimized grid for each paper plane study

Velocity magnitude (equivalent to $Re=100,000$ at chord) is specified at the inlet with zero pressure boundary condition is enforced at the outlet. The angle of attack (α) for all paper plane is varied between -5° to 40° with 2° interval. The wing surface itself is modelled as a non-slip surface. The turbulence intensity is set at 5% with the automatic wall function was fully employed to solve the viscous effect. A steady state, incompressible flow Navier-Stokes equation (RANS) combined with Shear Stress Turbulence (SST) model were used to solve the turbulence viscosity problems over each paper plane design. The simulation convergence was control based on the magnitude of momentum residual (below 1.0×10^{-5}) and monitoring the value of lift (C_L) and drag (C_D) coefficients.

3. Results

3.1 Lift Coefficient (C_L) Results

Figure 6 presents the lift coefficient (C_L) results for Glider, Stunt Plane and Wide Stunt Glider paper plane. The results exhibit that each paper plane produce almost similar C_L distribution with the increment of α . At pre-stall angle (starts from zero lift angle to stall angle), each plane induces almost linear C_L distribution up to the maximum lift coefficient magnitude (C_{Lmax}) at stall angle. However, C_L magnitude begins to deteriorate with the increment of α after the stall angle (α_{stall}).

Based on the C_L magnitude, the results show that Stunt Plane shows better C_L magnitude compared to the other plane design at α cases between 0° to 15° . At this α range, the Stunt plane managed to produce at least 4.4% better C_L magnitude compared to the other plane design. However, as the α magnitude increase over 15° , the Stunt plane has lower C_L magnitude than the Glider and Wide Stunt Plane. The Glider has produced almost 12% better C_L magnitude than Stunt plane produced. Even, the Wide Stunt plane also managed to produce averagely 4% better C_L magnitude than Stunt plane at α cases over 15° . Analysis on the magnitude of zero lift angle ($\alpha_{L=0}$)

shows that the Glider paper plane produce the lowest $\alpha_{L=0}$ nearly at -2° . This is followed by the Wide Stunt and Stunt Plane at nearly $\alpha_{L=0} = -1^\circ$ and $\alpha_{L=0} = -0.5^\circ$, respectively. In terms of α_{stall} magnitude, the Glider paper plane also induced better stall angle compared to Wide Stunt Plane and Stunt Plane. The Glider paper plane delayed stall at $\alpha_{stall} = 32^\circ$ which is about 2° to 7° higher than the Wide Stunt Plane ($\alpha_{stall} = 30^\circ$) and Stunt Plane ($\alpha_{stall} = 25^\circ$). Based on these $\alpha_{L=0}$ and α_{stall} performances, the α envelope is determine based on the α range started from the magnitude of $\alpha_{L=0}$ towards α_{stall} . The results clearly exhibited that the Glider paper plane produced better α envelop compared to Stunt Plane and Wide Stunt Glider plane. The α envelop for Glider paper plane is 34° which is about 9.67% to 33.3% better than the α envelop produced by Stunt Plane and Wide Stunt Glider Plane, respectively. The investigation of C_L performance continues by evaluating the C_{Lmax} performances for each paper plane design. The results show that the Glider paper plane has the highest C_{Lmax} magnitude at $C_{Lmax} = 1.246$. This is followed by the Wide Stunt Glider and Stunt paper plane at $C_{Lmax} = 1.136$ and 1.067 , respectively. Thus, the Glider paper plane has at least 9.68% better C_{Lmax} magnitude compared to the other paper plane designs considered in this works. Based on these C_L results, one can presumed that the Glider paper plane has the best C_L performances among the paper plane designs. Despite of low aspect ratio magnitude (Glider's AR= 2.81), the Glider paper plane managed to produce better C_L (at α cases over 15°), α_{stall} , wider α envelope and higher C_{Lmax} magnitude.

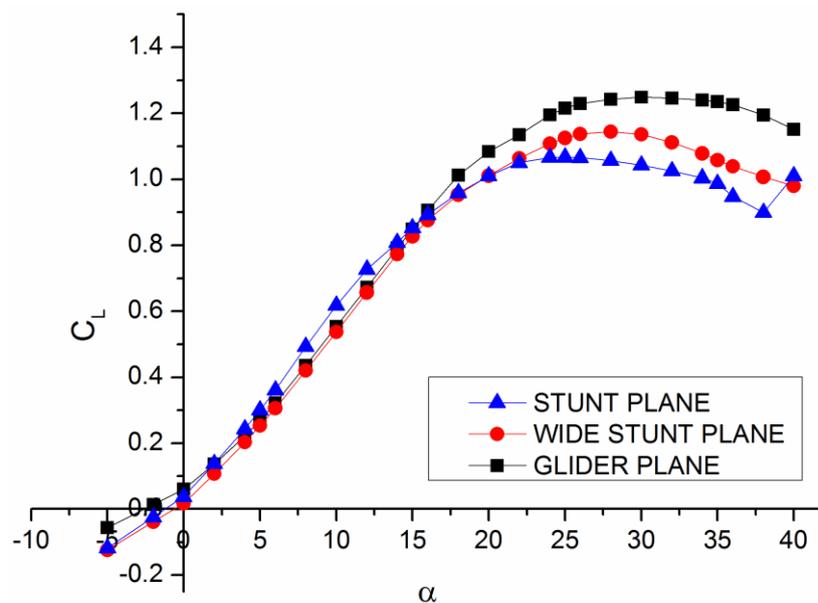


Fig. 6. Lift coefficient (C_L) results for Glider, Stunt Plane and Wide Stunt Glider paper plane

3.2 Drag Coefficient (C_D) Results

The Figure 7 presents the drag coefficient (C_D) results for Glider, Stunt Plane and Wide Stunt Glider paper plane. In overall, the results exhibit that each paper plane produce almost similar C_D trend towards the increment of α . C_D magnitude for all paper plane increase with the α increment. At low α region (between 0° to 15°), the results show that there is no clear difference in C_D magnitude among the paper plane. However, The Wide Stunt paper plane managed to produce averagely 5% lower C_D magnitude among the wing at this α region. As the α increase beyond 15° , the difference

in C_D magnitude is more obvious. The Glider paper plane has at least 14.3% larger C_D magnitude compared to the other plane design at this α region. The Stunt paper plane

The investigation on minimum drag (C_{Dmin}) performances reveal that the Wide Stunt Glider paper plane has surprisingly produced the lowest drag magnitude at $C_{Dmin}=0.0133$ (at $\alpha =0^\circ$). This is followed by the Glider and Stunt paper plane which produced $C_{Dmin}= 0.0246$ (at $\alpha =-2^\circ$) and 0.0185 (at $\alpha =0^\circ$), respectively.

Analysis of C_D increment between the paper planes was conducted to elucidate the drag performance among the paper planes. The analysis is divided into 2 α regions: low α region ($\alpha=0^\circ-15^\circ$) and high α region ($\alpha =15^\circ- \alpha_{stall}$). At low α region, the result shows that the C_D magnitude for Glider paper plane increase about 31% for every 2° α changes. Wide Stunt Glider and Stunt plane produce about 41% and 36.7% increment at similar α changes. However, this C_D increments were reduced significantly to 12% (for Glider and Wide Stunt Glider) and 11% (Stunt) as the angle enter the high α region. Based on these C_D results, one can presumed that the Wide Stunt paper plane has more promising C_D performances among paper planes. Despite of large C_D increments, Wide Stunt has promisingly produced lower C_D value (at α region below 15°) and lower C_{Dmin} magnitude compared to the other plane design.

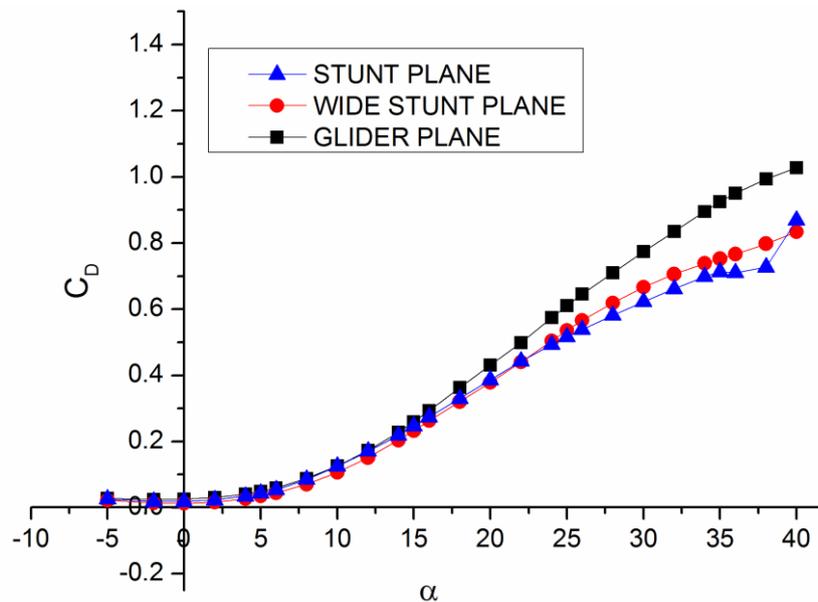


Fig. 7. Drag coefficient (C_D) results for Glider, Stunt Plane and Wide Stunt Glider paper plane

3.3 Aerodynamic Efficiencies (C_L/C_D) Results

Figure 8 presents the performance of aerodynamic efficiencies (C_L/C_D) for each paper plane design considered here. In overall, all paper plane induced almost similar trend of C_L/C_D curve with the increment of C_L magnitude. The magnitude of C_L/C_D increase almost linearly at early C_L increment which is between $C_L=-0.056$ to 0.269 which equivalently at α between -5° to 5° . The C_L/C_D magnitude reach its maximum value (known as C_L/C_{Dmax}) at $C_L=-0.056$ to 0.222 or which α between 2° to 5° . However, as the C_L increase further (or $\alpha > 5^\circ$), the C_L/C_D performances for each design is gradually drop towards the stall condition at C_L between 1.067 to 1.246 (or α between 25° to 32°). Based on the overall C_L/C_D performance, the result clearly shows that the Glider paper has the lowest C_L/C_D magnitude in almost every C_L cases. The design averagely produced at least 5.69%

lower C_L/C_D magnitude compared to the other design. On the other hand, Wide Stunt paper plane has averagely produced at least 1.82% better C_L/C_D magnitude compared to the other design.

Comparative analysis was also conducted by focusing on the difference in C_L/C_{Dmax} magnitude among the paper plane. The result clearly shows that Wide Stunt paper plane induced the best C_L/C_{Dmax} magnitude among the paper plane at $C_L/C_{Dmax}=6.32$. This condition happens at $C_L=0.108$ and relatively at $\alpha=2^\circ$. This is followed by Stunt paper plane at $C_L/C_{Dmax}=5.94$ which relatively occurred at $C_L=0.138$ and $\alpha=2^\circ$. The Glider paper plane induced the lowest C_L/C_{Dmax} magnitude among the paper plane at $C_L/C_{Dmax}=5.45$. This is happening at $C_L=0.269$ and $\alpha=5^\circ$. Based on these results, it clearly shows that Wide Stunt paper plane induced at least 6.4% better C_L/C_{Dmax} magnitude compared to the other paper plane design. In fact, the C_L/C_{Dmax} magnitude for Wide Stunt paper plane is also produced at 3° earlier than the Glider paper plane. This means that optimal aerodynamic condition for Wide Stunt paper can be easily achieved with very minimal tilting α angle. These promising results is due to better C_D performance found on the Wide Stunt paper. Lower C_D value (at α region below 15°) and better C_{Dmin} magnitude has benevolently delayed the drag to overwhelm the lift distribution on the Wide Stunt paper plane design. On the other hand, despite of huge advantage in lift distributions, the the significant drag generation on the Glider plane design has overwhelm its lift performances which leads into lower C_L/C_D performances.

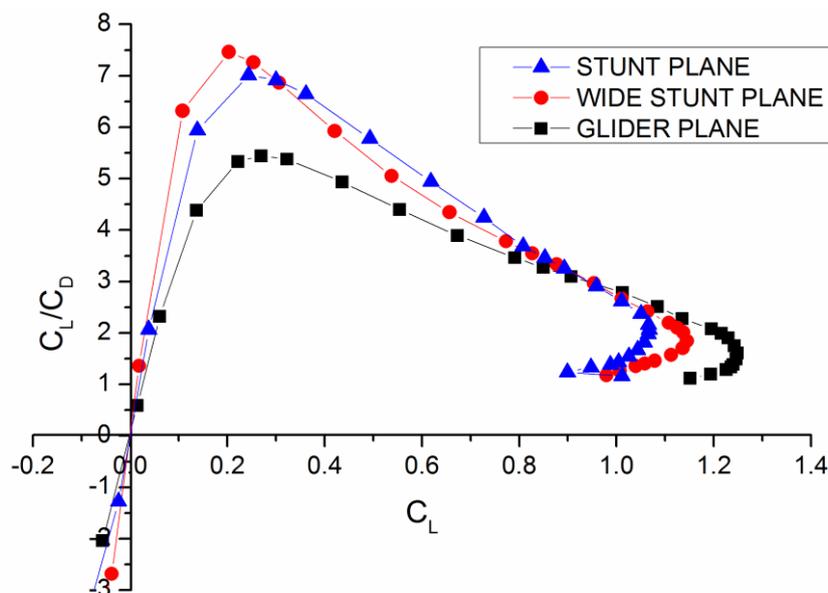


Fig. 8. C_L/C_D performance for Glider, Stunt Plane and Wide Stunt Glider paper plane

4. Conclusions

In this work the aerodynamic analysis on selected paper plane designs known as Glider, Wide Stunt Glider and Stunt plane was carried out. Based on CFD methods the results show that the Glider paper plane has surprisingly produces promising performances in C_L . Even at low aspect ratio magnitude (AR= 2.81), the Glider paper plane managed to produce better performances in the Glider paper plane managed to produce better C_L (at α cases over 15°), α_{stall} , wider α envelope and higher C_{Lmax} magnitude compared to the other paper plane design. Surprisingly, its promising advantages does not continue in C_D performances in which the Glider paper plane has at least 14.3% larger C_D magnitude compared to the other plane design at certain α region. Instead, The Wide Stunt has promisingly produced better C_D distribution based on its lower C_D value (at α region below 15°) and

lower C_{Dmin} magnitude compared to the other plane design. Based on C_L/C_D performance, Wide Stunt paper plane has clearly produced better C_L/C_D and C_L/C_{Dmax} magnitudes compared to the other design. Wide Stunt paper plane induced at least 6.4% better C_L/C_{Dmax} magnitude compared to the other paper plane design. In fact, the C_L/C_{Dmax} magnitude for Wide Stunt paper plane is produced at 3° earlier than the Glider paper plane. Based on these results, one can conclude that Wide Stunt paper plane shows promising advantages in producing better aerodynamic efficiency at lower α angle. Such advantages are very crucial for the paper plane especially during hovering operation, take-off, and landing manoeuvre.

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